Materials and Structures (2020) 53:74
https://doi.org/10.1617/s11527-020-01511-x

ORIGINAL ARTICLE

Fatigue behaviour of macrofiber reinforced gap graded asphalt mixtures

Francisco Morea · **Miguel Sol-Sanchez** · **Fernando Moreno-Navarro** · **Raúl Zerbino**

Received: 11 December 2019 / Accepted: 16 June 2020 / Published online: 26 June 2020

Abstract The addition of fibres to reinforce asphalt mixtures is a prospective field for pavement engineering, where the use of glass or synthetic macrofibers could potentially help not only as reinforcement for new asphalt mixtures, but also as part of asphalt overlays applied on deteriorated pavements to diminish reflective cracking during maintenance operations. In recent studies, it has been found that the addition of macrofibres can improve the rutting and fracture resistance of asphalt mixtures. However, the response of these mixtures to fatigue has not been studied yet. In this study, a complete performance characterization of a gap graded asphalt mixture with the addition of glass and synthetic macrofibres was studied. Also, a reference asphalt mixture without macrofibres was provided for comparison. Results showed that the addition of macrofibres improves water sensibility, rutting performance and stiffness of the gap grade asphalt mixtures studied. Also, it was observed during the fatigue tests that the incorporation of both types of macrofibres greatly improved the durability of the mixtures to fatigue cracking at medium range temperatures. This improved fatigue behaviour correlates to an extended useful life for the fibre reinforced asphalt mixtures. The synthetic macrofibres showed better fatigue behaviour at lower temperatures, while glass macrofibres gave a better response at the higher temperature studied.

Keywords Macrofibers · Gap grade asphalt mixture · Fatigue · Rutting · Stiffness

F. Morea (✉) · R. Zerbino
Construction Department, Engineering Faculty, National University of La Plata and CONICET, 1 Street and 47 Street, 1900 La Plata, Argentina
e-mail: francisco.morea@ing.unlp.edu.ar; franciscomorea@conicet.gov.ar

R. Zerbino
e-mail: zerbino@ing.unlp.edu.ar

M. Sol-Sanchez · F. Moreno-Navarro
Construction Engineering Laboratory of the University of Granada (LabIC.UGR), Severo Ochoa w/n, 18071 Granada, Spain
e-mail: msol@ugr.es

F. Moreno-Navarro
e-mail: fmoreno@ugr.es

1 Introduction

Asphalt mixtures are used as the base and surface layers of flexible pavements. Accordantly with Pereira and Pais [1], they are one of the most expensive elements of road construction and are also the highest cost element for maintenance operations, apart from the bridges and viaducts. These flexible layers have the role of supporting the traffic and climate conditions. With regard to traffic induced stress, the mechanistic-empirical design approach was conceived by Dormon and Metcalf [2], essentially calculating the pavement structure response (stresses and strains) to one or more distresses (cracking and permanent deformation), as a function of the material's properties, layer thickness and loading conditions. However, the effect of the climate also influences the performance of the pavement during its service life [3]. In particular, the presence of environmental phenomena could considerably alter the mechanical properties of the bituminous materials of pavement reducing its strength and bearing capacity [4]. Nowadays the design process evaluates the asphalt mixture's performance taking into account the different situation that pavement potentially suffers in its life. For example, the new Mechanistic-Empirical Pavement Design in United Stated [5] incorporated calibrated models to predict distinct distresses induced by traffic loads and environmental conditions. In the same way, Europe develop its mechanical–empirical design method as well [6–8].

For these reasons, improved asphalt mixtures and tools to properly select them are essential. A way to improve the performance of mixture is adding different materials [9–11], for example different kinds of fibres [12–16]. The most commonly fibres employed in asphalt mixture are the cellulose fibres in stone mastic asphalt (SMA) and porous asphalts to attain a higher asphalt content without it draining down during the mixing and placement process [17, 18]. However, fibres can have other functions like controlling the cracking process and improves the toughness, residual stress capacity and tensile strength. In consequence improving asphalt mixture performance and durability.

Many investigations have reported advances in behaviour of Fibre Reinforced Asphalt Concretes (FRAC) [3, 19–31]. However, all mentioned works refer to short fibres (length < 25 mm, less than the maximum size of the aggregate). There are few studies incorporating macrofibres (length > 25 mm) available in the literature and no field applications of this type of mixture, at least to the author's knowledge. The action mechanism and improvements of macrofibres in the field of asphalt mixtures are still very much unknown, while in recent research works [32, 33], it was shown that the addition of macrofibres can improve the behaviour of mixtures against rutting and cracking. It was found that the incorporation of fibres improves the rutting behaviour observing a reduction in final deformation [32]. Regard fracture there was found that at low temperature, where the asphalt concrete has a more brittle behaviour, the fibres develop an important role act as a bridge once the crack is former transferring the stress and consequently developing higher residual stress capacity [33].

Nonetheless, other performance aspects of these types of FRACs (with macrofibres), like stiffness, water sensitivity and fatigue behaviour have yet to be thoroughly studied. Thus, this work focuses on the study and characterization of the behaviour of a high-performance asphalt mixture, more specifically a gap grade asphalt mixture reinforced with different types of macrofibres (glass and synthetic). Performance properties like stiffness, resistance to fatigue cracking, water sensitivity, rutting and loss of mass in abrasion test were assessed.

2 Experimental

2.1 Materials

The study was developed starting with a gap grade asphalt mixture, BBTM11B, according to Spanish Standard PG3 [34] and EN13108-2 as show in Fig. 1. This control mixture was made using a coarse ophitic aggregate (6–12 mm), crushed limestone sand (0–6 mm) and cement as filler, with all granular materials fitting the requirements for the manufacturing of this type of mixture. As binder, a bitumen modified with SBS polymers (PMB-SBS: penetration 45/80 0.1 mm, softening point of 65 °C) was used. This mixture was designed according to the

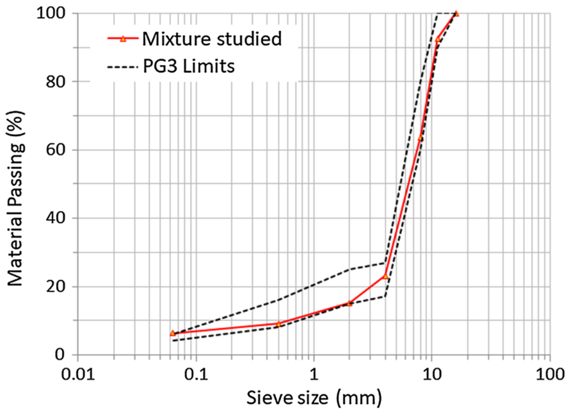

Fig. 1 BBTM 11B aggregate gradation

specifications of the Spanish Standard—PG3 [34] for this type of mixture.

On the other hand, to assess the potential reinforcement of this type of mixture, two types of macrofibres, glass and synthetic, were employed in this study. The main characteristics of the fibres can be observed in Table 1, while a better understanding of the definition of macrofibres and their performance in asphalt mixture can be found in previous works [32, 33]. Thus, in addition to the control mixture (BBTM) other two macrofibres reinforcement asphalt mixtures were studied: BBTM G and BBTM S for glass and synthetic macrofibres, respectively.

The main design characteristics of the mixtures are shown in Table 2. The dosage of each fibre used was based on the results founded in our previous works [32, 33] and trying to incorporate a similar volume of fibres in both FRACs. The reduction in air void content when using fibres must be related to the volume occupied by these components since it is also seen that the voids in the mineral aggregate remained similar between the different mixtures, and then, indicating similar compaction of the mixtures.

Therefore, the volumetric compositions of the mixture are comparable since their structure was similar (with similar binder content and dosage of aggregates), but including the fibres. This was the main objective pursued is this study. Nonetheless, due to the effect that the air void content can present on the performance of the mixture according to previous studies like [35], it will be considered for the results analysis.

2.2 Testing program

The main objective was to evaluate the potential improvement in the mechanical performance of asphalt mixtures when either glass or synthetic (polyolefin) macrofibres are incorporated. The different asphalt performances were characterized in regard to rutting, stiffness, fatigue cracking, water sensitivity and abrasion. Table 3 shows the testing plan followed. A particular emphasis was made in the fatigue response of the FRACs, which could be a key factor to determine the influence of macrofibres on the service life of the bituminous materials.

2.2.1 Wheel tracking test

The rutting performance was evaluated through the Wheel Tracking Test (WTT). The test procedure was configured according to EN 12697-22 “small size device” standard. Wheel tracking slope (WTS) and proportional rut depth (PRD), Eqs. (1) and (2) respectively, were calculated as WTT results.

$$\mathrm{WTS} = \frac{D_{10,000} - D_{5000}}{5}\,[\mathrm{mm\ per\ } 10^3 \mathrm{\ cycles}] \tag{1}$$

$$\mathrm{PRD} = \frac{D_{10,000}}{h} 100\,[\%] \tag{2}$$

where D_{5000} and $D_{10,000}$: permanent deformation at cycles 5000 and 10,000, respectively; h: sample height.

2.2.2 Dynamic modulus

The stiffness modulus of the different asphalt mixtures studied were measured at 5, 20 and 40 °C following the EN 12697-26 annex C standard to evaluate their bearing capacity and the influence of macrofibres in the mixture at different temperatures.

Table 1 Macrofibre properties

Fibre	S	G
Type	Synthetic (polyolefin)	Glass
Length (mm)	55	36
Density (g/cm^3)	0.91	2.68
Aspect ratio (L/Ø)	60	67
Tensile strength (MPa)	560	1700
Elastic modulus (GPa)	3.9	72
Melting point (°C)	155–165	860
Dosage (% of weight in mix) (%)	0.3	0.4

Table 2 Properties of asphalt mixtures studied

Properties	Bituminous mixtures		
	BBTM	BBTM G	BBTM S
Coarse aggregate (6–12 mm)	Ophite (70.5%)[a]		
Fine aggregate (0–6 mm)	Limestone (19.1%)[a]		
Filler	Cement (5.7%)[a]		
Asphalt binder	PMB-SBS (4.75%)[a]		
Fibre dosages (%)	–	0.4	0.3
Bulk density (g/cm^3)	2.301	2.413	2.385
Air voids (%)	17.5	13.4	14.4
Void in the mineral aggregate (%)	27.1	27.5	27.4
Stiffness at 20 °C, rise time value 124 ± 4 ms, 0.91 EN 12697-26-C (MPa)	2102	2822	2779
Indirect tensile stress at 15 °C (kPa)	1089.4	1456.8	1595.0

[a] The same quantity was used in all mixture

Table 3 Testing plan developed over each asphalt mixture studied

Test	Standard	Load (kN)	T (°C)	F (Hz)	Sample tested	Observation
Wheel tracking	EN 12697-22 Small size device	0.7	60		2	26.5 cycles per minute
Stiffness modulus	EN 12697-26 Annex C		5	10	3	
			20	10	3	
			40	10	3	
Water sensitivity	EN 12697-12		15		6	One group of three samples conditioning at 40 °C for 68–72 h One group of three samples as control
Abrasion	EN 12697-17		25		3	
Fatigue in UGR FACT	[36]	0.4	10	5	3	
			15		3	
			20		3	

2.2.3 *Water sensitivity test*

Regarding moisture damage on asphalt mixture, fibres can help to minimize this. Thus, water sensitivity, denoted as indirect tensile strength ratio (ITSR) at 15 °C, was determined according to EN 12697-12.

2.2.4 *Abrasion test: "Cantabro" test*

Abrasion test is specified into the design for this type of gap grade asphalt mixture (BBTM 11B). The loss of mass of asphalt mixtures was assessed by mean of the abrasion test (EN 12697-17) and was considered to observe how macrofibres act in this aspect.

2.2.5 *Fatigue test*

Fatigue response was studied with the equipment Fatigue Asphalt Cracking Test of Granada University (UGR-FACT) [36]. This test provides a global understanding of the fatigue-cracking phenomenon by reproducing the service conditions (both traffic loads and thermal gradients) expected in road pavements. The test was conducted at 10 °C, 15 °C, and 20 °C since temperature plays an essential role in the performance of bituminous materials. The test was carried out for specimens with dimensions of 220 mm of length, 60 mm of width and 40 mm of height, applying stress-controlled conditions (cyclic loading with a stress amplitude of 0.4 MPa and a frequency of 5 Hz) in order to simulate the real conditions usually endured by the pavement, along with the effects of high-speed traffic.

The UGR-FACT reproduces the efforts that lead to the failure of the pavement. The test device is composed of a base (Fig. 2a), two supports where the specimen is fixed (Fig. 2b), and a load application plate (Fig. 2c). The base has a platform that is composed of two sloping surfaces with two rails that allow for the sliding of the supports, and of two vertical spindles that are used to measure vertical deformations in the upper part of the test specimen (Fig. 2d). The two supports are composed of a carriage that is adapted to the shape of the rail at the base (leading to effective load transmission), and a support plate (to which the test specimen is attached with epoxy resin) where the horizontal deformation gauges (LVDT) are located (Fig. 2e). Furthermore, under these support plates, two elastic elements are introduced in order to allow for the flexion of the specimen (Fig. 2f) and a spring that simulates the foundation layers (Fig. 2g). The distance between the supports can vary, depending on the type of deterioration that needs to be reproduced (e.g. a crack, pre-crack, dilatation joint, pothole, etc.). Finally, the head of the load application is composed of a piece of steel that is thick enough to prevent deformations during the load application (thus avoiding differential errors due to its own deformation, which are unrelated to the test specimen) whilst providing a flat surface for the vertical deformation gauges (Fig. 2f).

The simple geometry of the test device is capable of generating horizontal as well as vertical deformations in the test specimen, which reproduce the bending and shear stresses due to traffic loading, as well as tensile strains due to the effect of thermal gradients (Fig. 2).

Thus, the test method is able to generate and propagate a controlled fatigue cracking process, and its evolution is studied through the dissipated energy in a representative volume of the specimen where the phenomenon takes place, avoiding its randomness and tridimensional dispersion. The results are expressed in terms of dissipated energy, and the damage produced in the specimen is quantified in accord with the fact that only the difference in dissipated energy from one cycle to another causes degradation in the material.

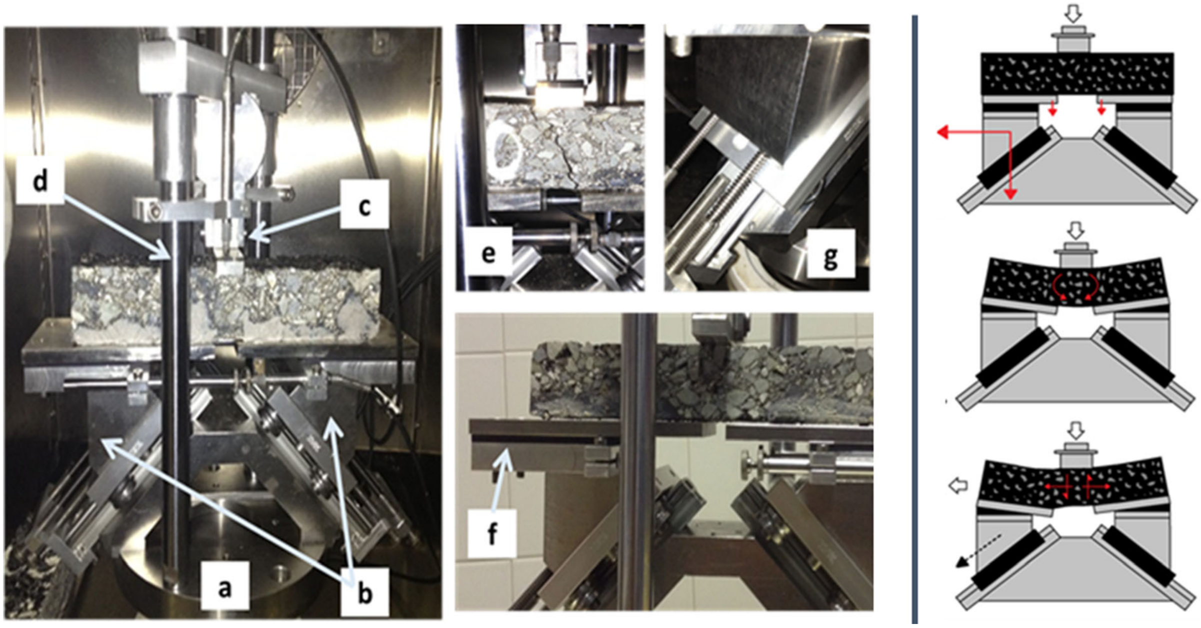

Fig. 2 UGR FACT equipment

Thus, the cumulative ratio of dissipated energy change (RDEC, Eq. 3) is used to analyze the evolution of the damage produced in the specimen, and the mean damage parameter (γ, Eq. 4) is a value used to establish a reference for the resistance to fatigue cracking of the pavement.

$$\mathrm{RDEC}_{n+1} = \frac{\omega_{n+1} - \omega_n}{\omega_n} \qquad (3)$$

where ω_n is the energy dissipation produced in loading cycle n (in J/m^3); and ω_{n+1} is the energy dissipation in loading cycle $n + 1$ (in J/m^3).

$$\gamma = \frac{\sum_{i=1}^{N_\mathrm{f}} \mathrm{RDEC}_i}{N_\mathrm{f}} \qquad (4)$$

where N_f is the failure cycle of the specimen.

3 Results and discussion

In the first stage, the gap grade asphalt concrete selected (with and without macrofibres) was fully characterized for stiffness, rutting, water sensitivity and loss of mass. Table 4 shows the mean stiffness values at different temperatures for mixtures used in this study in order to assess the effect of the fibres on the bearing capacity of the bituminous material. An increase in the stiffness can be observed at all temperatures studied for FRACs in comparison with the control BBTM, which indicates higher bearing capacity, although it must be also considered that this could be associated with the reduction in air void content of these mixtures, in consonance with previous studies [35].

Table 4 Stiffness of asphalt mixtures at different temperatures

T (°C)	Stiffness (MPa)		
	5	20	40
BBTM	7850.4	2102.0	496.7
SD	± 562.7	± 193.2	± 37.4
BBTM S	9399.6	2779.6	582.8
SD	± 1014.6	± 403.7	± 31.23
BBTM G	8266.2	2822.0	673.8
SD	± 785.9	± 289.3	± 58.4

SD standard deviation

When comparing the stiffness of both macrofibres asphalt mixtures, BBTM G shows less thermal susceptibility than BBTM S since the first one recorded a lower reduction in stiffness when increasing temperature. Also, generally speaking, the BBTM with glass macrofibres showed a higher stiffness than BBTM S at the high temperatures studied (20 and 40 °C) and lower stiffness at 5 °C, which could lead to better behaviour (considering the relation of this parameter with other properties like resistance to both permanent deformations and cracking). Nonetheless, it must be considered that both reinforced mixtures present similar stiffness values.

On the other hand, results from the wheel tracking test (Fig. 3; Table 5) showed that the macrofibre asphalt mixtures led to improvements in rutting behaviour in comparison with the control mixture. Particularly, Fig. 3, which displays the evolution of the rut depth with the number of wheel passes, reflects that the inclusion of fibres led to lower deformations during the beginning stage of the tests while also reducing the tendency to long-term ruts. This could be related to the fact that the macrofibres probably act in two ways regarding permanent deformations: first generate an interlocking of coarse aggregates; and second increase the mass viscosity of the mastic. Both mechanisms improve the asphalt mixture resistance. In Fig. 4 can be see how synthetic macrofibre do not melt totally when were incorporated to the mixture. This could be due to the short interaction time at high temperature, and therefore, they conserve its fibre form. This is in consonance with found in previous studies [33].

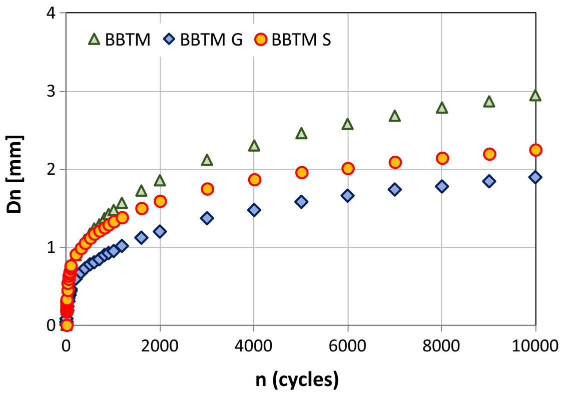

Fig. 3 Rutting against loading cycles for WTT of mixture studied

Table 5 Result of other performance test characterization

Test	BBTM	BBTM G	BBTM S	PG3 standard limits
Rutting (EN 12697-22 B)				
Depth at 10,000 cycles (mm)	2.96	1.90	2.25	
PRD (%)	7.5	4.9	5.6	
WTS (mm/10^3 cycles)	0.099	0.062	0.058	< 0.070–0.10
Water sensitivity (EN 12697-12)				
ITSR (%)	90.3	93.6	97.0	> 90
Abrasion (EN 12697-17)				
Dry loss of mass (%)	7.5	6.7	8.1	< 20

PRD proportional rut depth, *WTS* wheel tracking slope, *ITSR* indirect tensile strength ratio

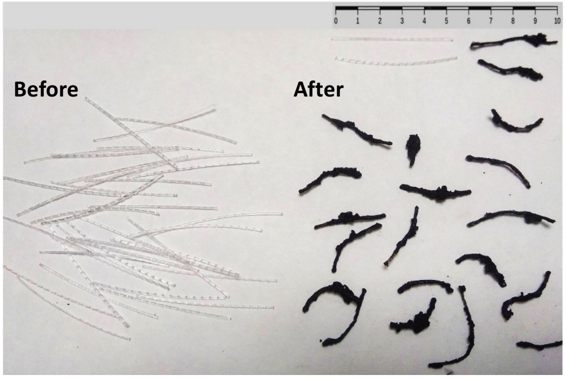

Fig. 4 Synthetic macrofibres before the mixing process

The positive effect of macrofibres is clearly noted in the decrease of the WTS values of BBTM G and BBTM S in comparison to BBTM, see Table 5. This is significant when bearing in mind that this kind of gap graded asphalt mixture is used as surface mixture and is submitted to high stress traffic loading. Regarding the influence of the type of macrofibre, the BBTM G showed lower WTS and this can be related with the higher stiffness of this asphalt mixture. Also, an important decrease in the PRD value of FRACs (35% and 25% for the BBTM G and BBTM S, respectively) can be seen in comparison with the control BBTM. The incorporation of both fibres leads to lower deformation values, which denotes the positive effect of these materials.

Table 5 also shows the results of water sensitivity and abrasion tests. All mixtures present excellent abrasion results that adequately meet the standard requirements. Regarding water sensitivity, all asphalts meet the requirements of standard EN 12697-12. Nonetheless, it can be noted that the control BBTM barely complied with the standard limit while both FRACs showed better responses. Therefore, it can be said that the macrofibres improved the cohesion and limited the debonding between asphalt and aggregate in relation to water sensitivity.

In order to analyse the effect of the macrofibres on the resistance to fatigue cracking of the mixtures, Fig. 5 shows the mean values of cycles to failure at the different testing temperatures. It can be observed that the addition of macrofibres extended the life of asphalt mixtures improving their fatigue behaviour. Meanwhile the BBTM fatigue life was reduced with an increase in temperature from 10 to 15 °C, whereas the BBTM G and BBTM S maintained their fatigue life at this temperature gradient, presenting higher number of cycles to failure than the control BBTM. Nonetheless, it must be considered that at 20 °C the fatigue life is similar between BBTM and BBTM S, but the BBTM G still showed higher fatigue resistance that the other two asphalt mixtures studied (more than double the fatigue cycles). These results could be related to the fact that at 10 and 15 °C, the synthetic macrofibres allowed for increasing the strength of the mixture due to their more elastic behaviour at such

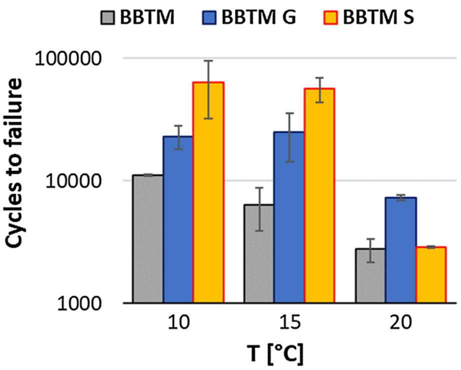

Fig. 5 Mean values of cycles to failure of fatigue test at different temperatures

temperatures, but when reaching 20 °C, they could no longer show this capacity to increase the elasticity of the material. On the other hand, as the glass macrofibres are stiffer than the synthetic ones, they led to higher improvement of the fatigue resistance when increasing the test temperature.

As fatigue resistance and dissipated energy by the materials are correlated, Fig. 6 shows the evolution of this last parameter against the cycles during the fatigue test in the UGR FACT. It can be seen how in some samples of BBTM G and BBTM S the evolution of dissipated energy is stabilized or even is reduced in contrast to the behaviour of BBTM samples.

Normally, it is expected that the dissipated energy increases until failure. However, when was analysed the progress of dissipated energy and the delta of horizontal strain against cycles in fibre mixtures studied at 10 °C, it was found that both variables showed a stabilization process (or even reduction) at the same cycle number in all samples studied. This could be explained in how macrofibres are expected to behaves when undergoing a cracking process. It is expected that macrofibres start to act when the microcracking is developed into the asphalt. Then, the fibres that cross the cracks take and transfer the load between both sides and maintain or reduce the crack opening displacement. This is normally referred to as the fibres “sewing the crack”. In consequence, the deformation balance changes and consequently the dissipated energy. This was more clearly noted at 10 °C than at the other two temperatures studied. Nonetheless, it must be considered that the influence or magnitude of this effect depends on the orientation and quantity of fibres crossing the cracks, the stiffness of fibres and the adherence between asphalt binder and fibres. This explain the scattering saw in the different sample of fibre mixtures.

Regarding the influence of the type of fibres, it was found that, generally, the synthetic macrofibres improved the fatigue life more than the glass macrofibres as can be seen in Fig. 6, which could be related to a higher adherence with the asphalt than glass macrofibres. Nonetheless, as the glass macrofibres are stiffer, they also produce an increase in fatigue life in comparison to BBTM, while allowing for better fatigue behaviour at higher temperatures (for example at 20 °C as seen in Fig. 5) than the synthetic macrofibres.

Another way to analyse the fatigue behaviour from the UGR FACT is by calculating the mean damage parameter (γ). In Fig. 7, the relation between γ and temperature can be seen for the different asphalts studied. The BBTM had higher mean damage values than the macrofibre reinforced asphalts (BBTM G and BBTM S) for all temperatures studied. Analysing the

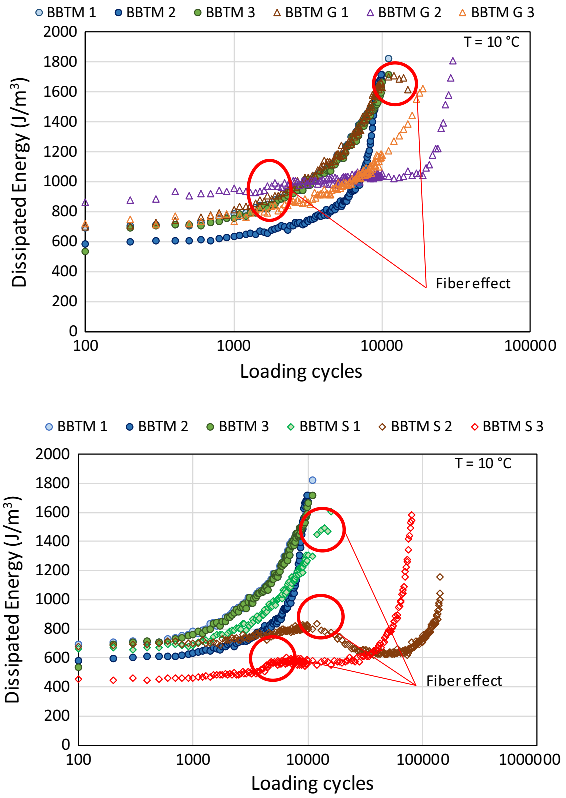

Fig. 6 Dissipated energy against loading cycles of the asphalt mixtures studied

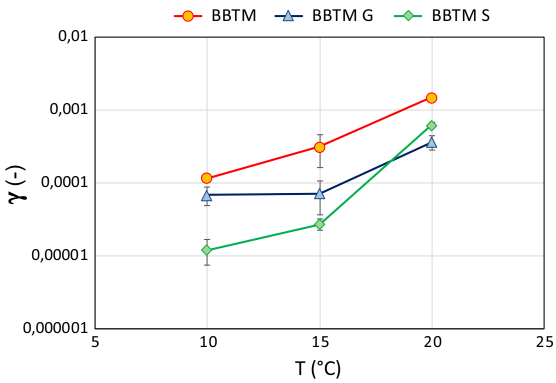

Fig. 7 Mean damage parameter at different temperatures of asphalt mixtures

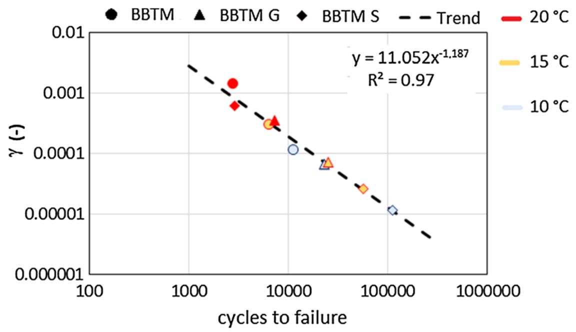

Fig. 8 Mean damage parameter against cycles to failure

progression, γ increased with the temperature more rapidly in BBTM than in the FRACs. The BBTM was more prone to fracture as temperature increased and damage occurred rapidly. In contrast, the macrofibres reinforced the asphalt matrix and played an important role while test temperature increased. Even so, it can be confirmed that the synthetic macrofibres gave a greater resistance (lower γ) at 10 and 15 °C than the glass macrofibres, but at 20 °C it was the glass macrofibres that gave a higher resistance than the synthetic ones. This behaviour is related to the adherence and stiffness of fibres as was mentioned and discussed before. According to the trend observed in Fig. 7, synthetic macrofibres could give excellent fatigue response at temperatures below 10 °C. This could be related with the more elastic behaviour of this kind of fibres.

In Fig. 8a clear correlation can be observed between the mean damage parameter (γ) and the cycles to failure of the different asphalt mixtures studied at different temperatures. The represented values are the mean for each condition tested. It can be seen in the figure that both FRACs had better responses than BBTM for each of the different temperatures represented.

4 Conclusion

This work primarily explores the potential improvements in asphalt mixture behaviour given by the addition of macrofibres as reinforcement, aiming to increase the mechanical performance of the material for its application in road pavements while extending its life. For this purpose, a series of laboratory tests were carried out to assess the influence of two types of macrofibres on the behaviour of a gap graded mixtures, focusing on the resistance to fatigue cracking where macrofibres could play an essential role. The main conclusions obtained are as follows.

As expected, the variation in temperature modified the fatigue behaviour; differential effects as a function of the temperature regarding the type of macrofibres were found. At low temperature (10 °C) synthetic macrofibres increased fatigue resistance while at normal temperature (20 °C) the glass macrofibres provide higher one.

- The macrofibres increase the asphalt mixture stiffness. The glass macrofibres mixture shows less thermal susceptibility than synthetic macrofibres mixtures.
- The incorporation of macrofibras enhance rutting behaviour, showing glass macrofibers the lowest reductions in depth the addition of macrofibres also impart some benefits on the water sensitivity performance. However, no significant differences were found between the effect of the type of fibres on the performance of the mixture in properties like water sensitivity, rutting and abrasion.

Therefore, there were confirmed potential positive effect of macrofibres on fatigue behaviour and consequent extension in the service life of asphalt mixtures, mainly due to effect of fibres allow a mechanism to sew the cracks. Although these benefits could be also associated with the reduction in air void content when using the fibres, it is important to mention that this phenomenon is mainly due to the volume occupied by the fibres, while the voids in the mineral aggregate and the asphalt binder ratio remain the same, and therefore, the volumetric compositions of the mixtures result comparable.

Acknowledgements The authors wish to thank and acknowledge the University of Granada and the National University of La Plata which made possible the development of this research. We would also like to give a special recognition to the doctor Gema García Travé for all her support during this research. A special recognition to Natalia Soledad Alvarez, nothing would have been possible without all your support. Rest in peace. With love Francisco.

References

1. Pereira P, Pais J (2017) Main flexible pavement and mix design methods in Europe and challenges for the

development of an European method. J Traffic Transp Eng 4(4):316–346

2. Dormon GM, Metcalf CT (1965) Design curves for flexible pavements based on layered system theory. Highway research record 71. Highway Research Board, pp 69–84
3. Navarro Moreno F, Sol-Sánchez M, Tomás-Fortún E, Rubio-Gámez M (2016) High-modulus asphalt mixtures modified with acrylic fibers for their use in pavements under severe climate conditions. J Cold Reg Eng 30:30–34. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000108
4. Haas R, Falls RC, Macleod D, Tighe S (2004) Climate impacts and adaptations on roads in Northen Canada. Cold climates conference, Regina, AB, Canada
5. National Cooperative Highway Research Program (NCHRP). (2004) Mechanistic-empirical design of new and rehabilitated pavement structures. NCHRP Project 1-37A. National Research Council, Washington, DC
6. European Commission (EC) (1999). European Commission (EC) Development of new bituminous pavement design method cost action, 333
7. Eberhardsteiner L, Blab R (2019) Design of bituminous pavements—a performance-related approach. Road Mater Pavement Des 20:244–258. https://doi.org/10.1080/14680629.2017.1380689
8. Blab R, Eberhardsteiner L, Haselbauer K, Marchart B, Hessmann T (2014). Implementierung des GVO- und LCCA-Ansatzes in die österreichische Bemessungsmethode für Straßenoberbauten [implementation of the performance-based approach and life-cycle cost analysis in the Austrian design method for bituminous pavements]. Bericht für die ASFiNAG (FFG-Projektnr. 2824558) **(in German)**
9. Angelone S, Martinez F, Cauhape Casaux M (2016) A comparative study of bituminous mixtures with recycled polyethylene added by dry and wet processes. In: 8th RILEM international symposium on testing and characterization of sustainable and innovative bituminous materials, RILEM Bookseries. https://doi.org/10.1007/978-94-017-7342-3_47
10. Moghadas Nejad F, Azarhoosh AR, Hamedi GHH, Azarhoosh MJ (2012) Influence of using nonmaterial to reduce the moisture susceptibility of hot mix asphalt. Constr Build Mater 31:384–388. https://doi.org/10.1016/j.conbuildmat.2012.01.004
11. Moreno-Navarro F, Iglesias GR, Rubio-Gámez MC (2016) Experimental evaluation of using stainless steel slag to produce mechanomutable asphalt mortars for their use in smart materials. Smart Mater Struct 25(11):115036
12. Musa N, Aman M, Shahadan Z, Taher M, Noranai Z (2019) Utilization of synthetic reinforced fiber in asphalt concrete—a review. Int J Civ Eng Technol 10(05):678–694
13. Tanzadeh J, Reza Shahrezagamasaei R (2017) Laboratory assessment of hybrid fiber and nano-silica on reinforced porous asphalt mixtures. Constr Build Mater 144:260–270. https://doi.org/10.1016/j.conbuildmat.2017.03.184
14. Xiong R, Fang J, Xu A, Guan B, Liu Z (2015) Laboratory investigation on the brucite fiber reinforced asphalt binder and asphalt concrete. Constr Build Mater 83:44–52. https://doi.org/10.1016/j.conbuildmat.2015.02.089
15. Kumar P, Sikdar PK, Bose S, Chandra S (2004) Use of jute fibre in stone matrix asphalt. Road Mater Pavement Des 5(2):239–249. https://doi.org/10.1080/14680629.2004.9689971
16. Hassan H, Al-Jabri K (2005) Effect of organic fibers on open-graded friction course mixture properties. Int J Pavement Eng 6(1):67–75. https://doi.org/10.1080/10298430500087936
17. Woodside A, Woodward W, Akbulut H (1998) Stone mastic asphalt: assessing the effect of cellulose fibre additives. In: Proceedings of the institution of civil engineers-municipal engineer, pp 103–108
18. Drüschner L, Schäfer V (2000) Stone mastic asphalt. German Asphalt Association, Berlin
19. Norambuena-Contreras J, Serpell R, Valdés Vidal G, González A, Schlangen E (2016) Effect of fibres addition on the physical and mechanical properties of asphalt mixtures with crack-healing purposes by microwave radiation. Constr Build Mater 127:369–382. https://doi.org/10.1016/j.conbuildmat.2016.10.005
20. Mohammed A, Hasan A (2016) Laboratory evaluation of modified porous asphalt mixtures. Appl Res J 2(3):104–117
21. Guo Q, Li L, Cheng Y, Jiao Y, Xu C (2015) Laboratory evaluation on performance of diatomite and glass fiber compound modified asphalt mixture. Mater Des 66:51–59. https://doi.org/10.1016/j.matdes.2014.10.033
22. Park P, El-Tawil S, Park S, Naaman A (2015) Cracking resistance of fiber reinforced asphalt concrete at – 20 °C. Constr Build Mater 81:47–57. https://doi.org/10.1016/j.conbuildmat.2015.02.005
23. Yoo P, Kim K (2014) Thermo-plastic fiber's reinforcing effect on hot-mix asphalt concrete mixture. Constr Build Mater 59:136–143. https://doi.org/10.1016/j.conbuildmat.2014.02.038
24. Qian S, Ma H, Feng J, Yang R, Huang X (2014) Fiber reinforcing effect on asphalt binder under low temperature. Constr Build Mater 61:120–124. https://doi.org/10.1016/j.conbuildmat.2014.02.035
25. Liu Q, Schlangen E, van de Ven M, van Bochove G, van Montfort J (2012) Evaluation of the induction healing effect of porous asphalt concrete through four-point bending fatigue test. Constr Build Mater 29:403–409. https://doi.org/10.1016/j.conbuildmat.2011.10.058
26. Serin S, Morova N, Saltan M, Terz S (2012) Investigation of usability of steel fibers in asphalt concrete mixtures. Constr Build Mater 36:238–244. https://doi.org/10.1016/j.conbuildmat.2012.04.113
27. Chen H, Xu Q (2010) Experimental study of fibers in stabilizing and reinforcing asphalt binder. Fuel 89:1616–1622. https://doi.org/10.1016/j.fuel.2009.08.020
28. Mahrez A, Karim M (2010) Fatigue characteristics of SMA reinforced with fibre glass. Int J Phys Sci 5(12):1840–1847
29. Arabani M, Amir Shabani A, Hamedi G (2019) Experimental investigation of effect of ceramic fibers on mechanical properties of asphalt mixtures. J Mater Civ Eng 31(9):04019203
30. Slebi-Acevedo C, Lastra-González P, Indacoechea-Vega I, Castro-Fresno D (2020) Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers. Constr Build Mater 234:117224. https://doi.org/10.1016/j.conbuildmat.2019.117224
31. González A, Norambuena-Contreras J, Storey L, Schlangen E (2018) Effect of RAP and fibers addition on asphalt

mixtures with self-healing properties gained by microwave radiation heating. Constr Build Mater 159:164–174
32. Morea F, Zerbino R (2018) Improvement of asphalt mixture performance with glass macro-fibers. Constr Build Mater 164:113–120. https://doi.org/10.1016/j.conbuildmat.2017.12.198
33. Morea F, Zerbino R (2018) Incorporation of synthetic macrofibres in warm mix asphalt. Road materials and pavement design. Published online 28 Jun 2018. https://doi.org/10.1080/14680629.2018.1487874
34. PG3: Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes de la Dirección General de Carreteras y Caminos Vecinales (PG-3/75). Ministerio de Fomento de España (2015)
35. Steiner D, Hofko B, Blab R (2016) Effect of air void content and repeated testing on stiffness of asphalt mix specimen. In: 7th civil engineering conference in the Asian region
36. Moreno-Navarro F, Rubio-Gámez MC (2013) UGR-FACT test for the study of fatigue cracking in bituminous mixes. Constr Build Mater 43:184–190